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Optimal bidding strategies in oligopoly markets considering bilateral contracts and transmission constraints

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Abstract

In electricity industry with transmission constraints and limited number of producers, Generation Companies (GenCos) are facing an oligopoly market rather than a perfect competition one. Under oligopoly market environment, each GenCo may increase its own profit through a favorable bidding strategy. This paper investigates the problem of developing optimal bidding strategies of GenCos, considering bilateral contracts and transmission constraints. The problem is modeled with a bi-level optimization algorithm, where in the first level each GenCo maximizes its payoff and in the second level a system dispatch will be accomplished through an OPF problem in which transmission constraints are taken into account. It is assumed that each GenCo has information about initial bidding strategies of other competitors. Impacts of exercising market power due to transmission constraints as well as irrational biddings of the some generators are studied and the interactions of different bidding strategies on participants' corresponding payoffs are presented. Furthermore, a risk management-based method to obtain GenCos' optimal bilateral contracts is proposed and the impacts of these contracts on GenCos' optimal biddings and obtained payoffs are investigated. At the end, IEEE 30-bus test system is used for the case study in order to demonstrate the simulation results and support the effectiveness of the proposed model.

Keywords: Bidding strategy; Oligopoly market; Market power; Bilateral contracts; Nash equilibrium; Transmission constraints

1. Introduction

The worldwide electricity industry is undergoing a movement towards new established markets based upon a competitive environment. These new electric markets enable the customers to buy their necessary power from different GenCos in order to achieve the lower rates and providing the power suppliers with the higher efficiencies. Two widely known markets the so-called pool and bilateral markets are employed in deregulated power markets. The former is a centralized market where both sellers and buyers participate simultaneously, while the latter is based on direct transactions between GenCos/marketers and consumers through pre-negotiated bilateral agreements. The main challenges that GenCos are dealing with in a centralized pool-based market is managing the optimal bidding strategies. Most of researches carried out in this area employing game theory to reach the Nash equilibrium. Accordingly, suppliers are able to utilize game-based algorithms to update and improve their cost functions to reach the Nash equilibrium point. Some of the relevant studies assume linear cost curves for participants when bidding into the market [1–3]. However some other works assume quadratic curves for both suppliers and consumers [4–7]. In fact there is no difference between linear and quadratic curves from participants' point of view [8] (As linear curves are derivatives of quadratic ones). In a centralized spot market participants may bid directly with their linear cost functions by altering corresponding characteristics that maximize their payoffs or they may bid with their quadratic cost functions by setting relevant coefficients in their quadratic curves. On the other hand suppliers may utilize these (quadratic or linear) cost curves to produce corresponding bid blocks in order to submit to the market. Similarly, some researches use linear cost curves to build bid blocks [8], while in some other ones, quadratic cost curves are applied to derive these bid blocks [4–6]. There are two types of games regarding: non-cooperative as well as cooperative games. In [3] a non-cooperative bidding strategy

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model is presented with incomplete information in which a supplier can bid some part of its capacity to the market, while self scheduling the remaining capacity. A non-cooperative transmission constrained bidding strategy with incomplete information is conducted in [7,8] that uses a bi-level optimization associated with DC optimal power flow. In [9] a market with no cooperation is modeled and a Cournot game is solved to simulate oligopoly market equilibrium. A non-cooperative game with incomplete information is employed in [10] that uses discrete bids, however no other constraint are taken into account. A cooperative game is employed in [11,12] to show the impact of coalitions and collusions among participants. In [13] a stochastic optimization model is used to develop optimal bidding strategies considering network congestion but no other transmission constraints as well as participants' market power are studied. Conejo et al. [14] presented a framework to obtain bidding strategy for price taker producers by estimating probability density function of market clearing price without considering network constraints. Fuzzy-c-mean and artificial neural networks are employed in [15] to determine bidding strategies of GenCos in a perfect competition environment without network constraints. In [16] the problem of building optimally coordinated bidding strategies for competitive suppliers in energy and spinning reserve markets is addressed. An imperfect market with uniform price is considered that transmission network limitations are not taken into account. A full competitive bidding strategy is addressed from the price point of view in [17] in which several boundary prices are defined such that generators can select their desired prices according to their attitude either risk averse or risk seeker. Finally a detailed literature review of bidding strategies in electricity markets is presented in [18]. All above mentioned researches, dealing with optimal biddings in a centralized spot market without considering bilateral transactions. In this paper the problem of developing optimal bidding strategies of GenCos in an oligopoly electricity market is proposed where bilateral contracts and transmission constraints are taken into account. Here it is assumed that suppliers bid to the market through updating their quadratic coefficients in their cost functions (that can be interpreted as the slope of corresponding linear cost functions). Furthermore GenCos are able to sign bilateral contracts as well as bidding to the pool market. In such combinatorial pool-bilateral market environment, in order to achieve a maximum profit GenCos should determine how much energy they should assign to bilateral contracts before bidding to a pool market. The problem is formulated as a two-level optimization in which the first level maximizes GenCos' payoffs and the second level deals with market clearing. The Primal Dual Interior Point Method (PDIPM) is applied for solving market clearing via an OPF. Finally, GenCos' optimal bidding strategies are derived based on the OPF sensitivity functions to reach the Nash equilibrium point. With the assumption of a complete information market, the impacts of exercising market power due to transmission constraints as well as irrational biddings of some generators are studied and the interactions of different bidding strategies on participants' payoffs are presented. A risk management-based method is proposed to obtain GenCos' optimal bilateral contracts and the impact of these contracts on GenCos' bidding strategies and corresponding profits are investigated.

The paper is organized as follows: the formulation of presented framework for a bidding strategy problem is given in Section 2, while the solution algorithm is presented in Section 3. A proposed risk management-based method for bilateral contract allocations is formulated in Section 4. Section 5 provides a case study and illustrates the simulation results of an IEEE 30-bus test system, and finally concluding remarks are given in Section 6.

2. Problem formulation framework

An imperfect competitive market is modeled in which GenCos may bid to a centralized pool market in order to reach the maximum profit, while considering transmission constraints. Assuming generator i has an operation cost function as:

$$C_{gi} = a_i {P_{gi}}^2 + b_i P_{gi} + c_i \tag{1}$$

Therefore the marginal cost of generator i will be:

$$\lambda_i = 2a_i P_{gi} + b_i \tag{2}$$

In such an oligopoly market, each generator is capable of bidding not necessarily with its marginal costs. In this case suppose that generator i bids with its quadratic coefficient (in the cost function) while other coefficients are constant as shown in Eq. (3):

$$C_{gi} = k_i {P_{gi}}^2 + b_i P_{gi} + c_i \tag{3}$$

where k_i is a bidding multiplier ($k_i \geq \alpha_i$). Assuming that there is complete information in which each GenCo has information of initial biddings offered by other competitors, the problem formulation is modeled with a bi-level optimization as follows:

$$\begin{aligned} \text{Max} \quad R_i &= \sum_{j=1}^{n_i} [\lambda_j P_{gj} - (a_j {P_{gj}}^2 + b_j P_{gj} + c_j)] \\ &= \lambda^{\mathrm{T}}_{\mathrm{Genco}i} P_{\mathrm{Genco}i} - (P^{\mathrm{T}}_{\mathrm{Genco}i} A_i P_{\mathrm{Genco}i} + B_i^{\mathrm{T}} P_{\mathrm{Genco}i} + C_i) \end{aligned} \tag{4}$$

$$\begin{aligned} &\text{Min} \quad \sum_{i=1}^{m} k_i P_{gi}^2 + b_i P_{gi} + c_i \\ &\text{s.t.} \quad \begin{cases} P_{gi} - P_{di} = \sum_{j=1}^{n} V_i V_j |Y_{ij}| \cos(\theta_i - \theta_j - \alpha_{ij}) \\ Q_{gi} - Q_{di} = \sum_{j=1}^{n} V_i V_j |Y_{ij}| \sin(\theta_i - \theta_j - \alpha_{ij}) \\ P_{gi\,\min} \leq P_{gi} \leq P_{gi\,\max} \\ Q_{gi\,\min} \leq Q_{gi} \leq Q_{gi\,\max} \\ V_{i\,\min} \leq V_i \leq V_{i\,\max} \\ P_{li\,\min} \leq P_{li} \leq P_{li\,\max} \end{cases} \end{aligned} \tag{5}$$